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INK JET PRINTING OF SILVER METALLIZATION FOR PHOTOVOLTAICS

Purdue Research Foundation

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JPL Flat Plate Solar Array Project

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FOREWORD

The research described in this report represents the effort for the second three months on Contract No. 957031 with the Jet Propulsion Laboratory, Pasadena, CA, under the technical cognizance of Paul Alexander. The research was conducted in the Turner Laboratory for Electroceramics, School of Materials Engineering and School of Electrical Engineering, Purdue University, W. Lafayette, IN under the direction of R.W. Vest. The research was carried out by Dr. S. Singaram, D.A. Binford, K.F. Teng and E.P. Tweedell.

1. INTRODUCTION AND SUMMARY

The development of the ink jet printing system continued throughout this quarter and significant progress was made in several areas. Many different tasks were studied by the staff of the Turner Laboratory involved in this project. All of these various aspects of the ink jet system's development will be covered in this report, and several major accomplishments are highlighted in the following paragraph.

As a follow up to the design modification studies, some decisions were made in order to meet future system goals. One of these goals is the implementation of some kind of computer aided design capability into the system. Another goal is to dramatically increase the printing speed, which requires programming acceleration and deceleration into the table movements. As the ink jet printing system gains the higher degree of sophistication necessary to accomplish these and other tasks, larger and larger amounts of memory storage will be required to contain the necessarily more complex software. It was decided that in order to meet the memory requirements, a floppy disk drive unit should be added to the system. This unit will not only supply the necessary general memory demands, but will also serve as a program input device, eliminating the system's current dependence upon a host computer. A 5.25 inch disk drive unit was ordered and received, but the job of getting it implemented into the system is significant. This task will be continuing into the next several months.

It is desirable to use some kind of computer aided design system with the ink jet printing system so that circuits designed on a graphics terminal could quickly be printed, fired, and tested. This would, of course, dramatically decrease prototyping time. Through a grant from Tektronix, Inc., the Turner Laboratory acquired a color graphics terminal which is the first step in reaching this goal. This model 4106 terminal will allow the use of a Purdue Engineering Computer Network interactive circuit design program called "CMASK". Some work was done this quarter to become familiar with both the new terminal and the "CMASK" program, but the task of putting the screen information in a form which the SCCS-85 board can interpret will require considerably more effort.

Another accomplishment this quarter was the completion of several improvements to the ink supply and pressure control system. In the past, some printing problems were experienced due to the inconsistent pressure in the ink bottle. It is this pressure which offsets a portion of the static vacuum in the ink head due to the level of the ink being below the level of the head. A low pressure regulator and two new pinch valves were added to the existing pressure control system. The regulator made a noticeable improvement in the pressure regulation in the ink supply bottle. The pinch valves were added to replace the existing Sporlan brand valves, which consumed a significant amount of power and caused some occasionally erratic microprocessor operation due to noise they caused on the power line.

During the last part of this quarter, some preliminary printing studies were started. Most of these were done on alumina substrates although a few test prints of the top side metallization on photovoltaic cells were conducted. These preliminary printings were conducted in order to evaluate how the system was working, and to begin to get some idea of how various solvents used with the MOD inks would affect the printing process. Some experimentation was also done with varying the head trigger frequency in order to try to increase the film thickness, hence improving sheet resistance. In the next quarter, much more work will be done along these lines.

Work continued during this quarter on program development. This work included investigating what additional programming will be necessary as increased printing speeds are tried. This involves giving the Superior Electric indexer boards acceleration and deceleration commands, and will also involve coordinating the table stepping frequency with the head triggering frequency. Other programs continue to be worked on. As an example, it is hoped that eventually the individual head nozzles will be turned on and off, as needed, by the SCCS-85 board. This could allow, for instance, a wide line to be printed in just one pass, thus further reducing the printing time.

Several other less significant improvements to the system were made this quarter, some on a temporary basis to test their effectiveness. An emphasis was placed on testing many of the ideas which resulted from the design modification studies of the first quarter. In the months ahead, the ideas which proved to work well will be implemented on a more permanent basis and investigation will continue in those areas where there are still problems to be worked out. Other changes will be made along the way as an attempt is made to make the ink jet system print efficiently and consistently. The remainder of this report describes, in detail, the accomplishments of this quarter and the proposed plans for the next quarter.

2. PROGRESS

2.1 Mechanical Modifications

There were several problems associated with the ink supply and pressure control system. One occasional, but very irritating, problem was that line transients caused by the solenoid valves turning on and off were causing erratic microprocessor operation. A check of the +5 volt supply line to the SCCS-85 board clearly indicated some significant spikes when either of the valves controlled by the Dwyer photohelic pressure switch/gauge cycled. These Sporlan brand valves operated on 115 VAC and consumed about 32 watts each. To alleviate this noise problem, two Angar brand valves part #401-NC-12-B-30 were purchased to replace the Sporlan valves. These new valves were installed and some rerouting of tubing was also done. The Angar valves operate on 12 VDC and consume only 3.9 watts each. These solenoid valves, which are normally closed, operate by pinching closed a 1/8 inch I.D. tube which passes between a set of jaws. When these valves are energized, the jaws separate and flow occurs. To further reduce noise generated by the switching, a 1N4001 diode was placed in parallel with each coil. These tend to clamp, to some degree, the turn on and turn off spikes associated with an inductor. The reduced power requirements of the new valves has all but eliminated the noise problems that were being experienced. Further noise protection is now being provided by a line transient protection device described in the next section. A small separate 12 volt power supply is being used on a temporary basis to power the two valves. These valves were connected to the Dwyer control unit in much the same way as the previous valves were. The inlet valve opens (energizes) only when the pressure drops below the lower set point. The exhaust valve opens (energizes) only when the pressure in the ink bottle rises above the upper set point. In this manner, with the set points set relatively close together, the Dwyer unit maintains a consistent ink bottle pressure.

The second pressure control system problem which had to be addressed was one which was severely degrading the accuracy of the system. The only regulation on the inlet side of the intake solenoid was a standard tank regulator having a range of 0-100 psi. It was incapable of regulating accurately below about 5 psi, particularly since its regulation was flow dependent. The result of this inaccuracy was that when the intake solenoid valve opened, a sudden pressure pulse entered the system causing the exhaust valve to open almost immediately to relieve this pressure. This, obviously, was defeating the whole idea of the regulating system. To correct this problem, a low pressure regulator was purchased and installed between the tank regulator and the intake valve. The unit chosen was a Rockwell model 043-180 which is set to regulate at 3.5 inches of water column. This unit's accuracy is also flow dependent, so a metering valve was added to the outlet side of the regulator and adjusted to allow a very small continuous gas flow when the system is being used.

The two above changes made a noticeable improvement in the pressure regulation in the ink bottle. This has, in turn, yielded more consistent printings since the pressure parameter can now be held very constant. The complete ink supply and pressure control system is pictured in Fig. 1. Several changes besides the ones described above are worth noting. In the original system there was a 450 cm^3 plastic container which acted as a buffer to dampen the sudden pressure pulse which occurred when the intake valve opened. This was eliminated after to the addition of the low pressure regulator. Secondly, the sense line for the Dwyer controller now comes directly from the ink bottle, giving better regulation accuracy. Note, also, the addition of a restrictive tube in the inlet line. This is to dampen the pressure pulse slightly when the intake valve opens because there is still some difference between the regulated inlet pressure and the maintained pressure in the ink bottle of approximatley 0.1 inch of water column. The manual purge valve is still used in much the same way it has always been. It is opened to prime the head initially with ink and to flush the head with a solvent when printing is completed.

In the past quarter, two micro switches were mounted on the positioning table in order to provide a means for positioning the table to an initial start point prior to each print sequence. Through programming and the use of JOG commands given to the indexer board, the table is positioned to an exact point below the print head before each printing sequence. This has proven to be a valuable addition to the system. When this change was first implemented, snap-action switches having a differential travel specification of 0.0010-0.0051 cm were used because they were immediately available and relatively inexpensive. However, because the table moves in increments of 0.00254 cm per step, it was

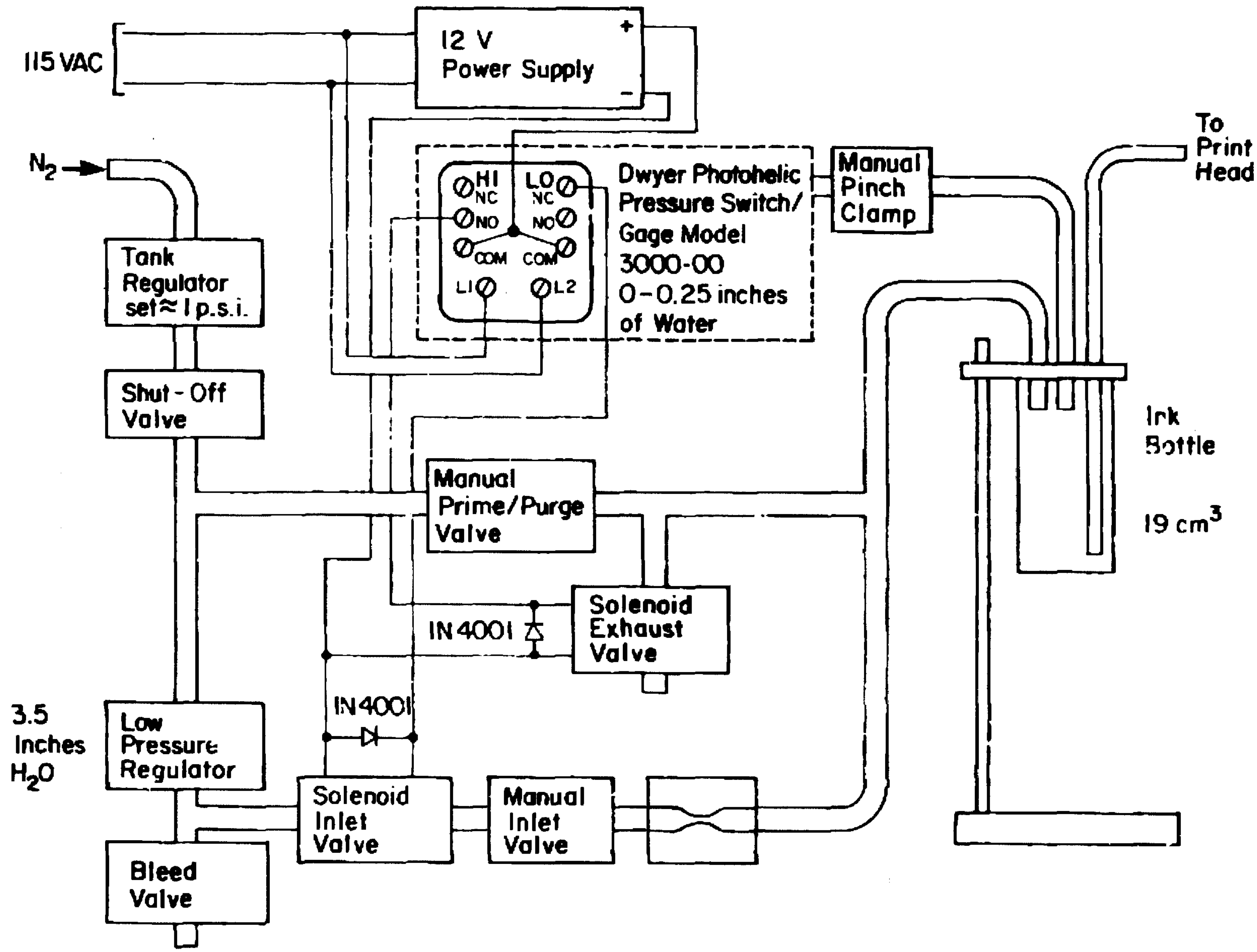


Figure 1 Ink Supply and Pressure Control System.

seen that a switch having a differential travel specification below this value was really what was needed to assure that the table was positioned to the same exact initialization point each time. Snap-action switches meeting these requirements were ordered shortly after the first switches were installed. During this quarter these type BZ-R-A2 switches from Micro Switch were received and installed on the table. The newer switches have a maximum differential travel specification of 0.0005-0.0008 cm. These higher precision units will yield more accurate, repeatable printings and will also allow precision multiple printings if desired.

2.2 Electronic Modifications

It has been determined that system memory will have to be significantly increased in order to meet future system goals. Currently, the SCCS-85 microcomputer board has only 4 kilobytes of RAM (random access memory). This is adequate for existing software but will fall short of meeting the requirements of the more complex programming which will be developed in the months ahead. To meet this requirement, a 5.25 inch, double sided, double density floppy disk unit was ordered and received during this quarter. The Teac model FD55B drive unit was decided upon after investigating what was going to be involved in getting it interfaced into the system. The designer of the SCCS-85 microcomputer board was consulted about how a disk drive might be interfaced with his board. Since he had previously done this very thing, he agreed to provide schematics for a disk controller/formatter. It was also learned that in order to use this disk interface board, a newer revision 3 version of the SCCS-85 would have to be obtained. The board which was being used was a SCCS-85 Rev.2 version lacking some additional control lines necessary for interfacing with the disk controller/formatter board.

A completely assembled SCCS-85 Revision 3 microcomputer board was located locally and purchased. Although assembled, it had not been tested. A small wiring error was located and corrected, and the other modifications necessary to adapt it to the ink jet system were performed. Due to a slight difference between the two boards, a small programming change had to be made for the board to operate the system correctly. With these changes in place, the newer Revision 3 unit is now a part of the system, hence completing the prerequisite for implementing the disk drive system.

All of the parts necessary to construct the disk controller/formatter board were ordered and most of them have been received. The actual construction has not yet started but this task and the job of testing and debugging the completed system will be completed within the next quarter. This will also involve some program writing to adapt a standard CP/M operating system to this particular system. Once this entire system has been put in place, the system will have a memory capability of 360 kilobytes, which should be more than enough for any future needs.

Completed this quarter was the selection and purchase of a power supply meeting most of the system power needs. A complete evaluation of these needs was done and maximum currents for each voltage used in the system were determined. This information was then used to select a model CP 167 linear regulated power supply made by Microcomputer Power, Inc. It will supply all the necessary system voltages except the +40 volts for the Siemens driver board and the isolated +12 and +24 volt supplies for the Superior Electric driver boards. The new power supply is a frame mounted unit with a cooling fan, and it will be incorporated into the system along with other changes which are being made to improve general system packaging and reliability. Part of the repackaging will involve rebuilding the power supply unit onto a standard width rack panel which will mount on the back side of the equipment cabinet. This will be done in such a way that the cooling fan will provide cooling for both the power supply components and for the Superior Electric Driver boards. This reconstruction may also involve the addition of multiple quick disconnect connectors so that the necessary DC voltages can be easily routed to the various subassemblies which are part of the system.

As an added precaution against line noise problems, a line noise suppression and transient protection device was purchased. It is a model RS 610 surge suppressor made by Perma Power. It incorporates both an L-C network for noise suppression and three metal oxide varistors for both normal mode and common mode transient protection. This unit is now being used between the 115VAC line and the main system power supply. Eventually, it will be incorporated directly into the new power supply assembly. Since the addition of this unit and the changing of the solenoid valves in the pressure control system, no significant noise related problems have been experienced. Future changes may be required, however, to further improve noise immunity.

During the design modification studies of the first quarter, it was decided to replace the LED displays used for indicating table position with LCD displays. This will further reduce the power requirements of the system. As part of this change, the new displays will be mounted on the same circuit board as the new counter/display driver integrated circuits. This assembly will be mounted on the rack panel which will contain all of the positioning table components. During this quarter, the counter/LCD display driver integrated circuits (National Semiconductor MM74C947) and the And brand FE0202D LCD displays were breadboarded and tested. The maximum currrent draw for one counter/display driver was 1 mA and it is more commonly in the 20-30 μA range, so there was a noticeable power reduction as compared to the LED displays.

Since the addition of the initialization switches to the table, there was a need for a circuit which would reset the counters when the table was positioned to its initialization point. Although the circuit has not yet been implemented, a design was successfully tested. The same lines from the switch 'debounce' circuits which activate the SCCS-85 interrupts will serve as the triggering signals for the reset circuits. These signals, which are positive going when the table switches are activated, will trigger 74LS123 retriggerable monostable multivibrators. Using external timing components, the 'one-shots' will be adjusted to output a pulse having a pulse width of 10 μs. The 'not' Q outputs of the IC's will connect to the 'not' RESET inputs of the counters. With these circuits in place, when the table switches are activated the counters will be reset to zero. Along with these reset circuits, circuits will be provided to reset the counters when power is applied. This feature will be accomplished with simple transistor circuits and a few timing components.

During the design modification studies of the first quarter, it was decided that some substantial effort should be put into improving general system packaging and layout. Careful layout and redesign could significantly reduce interwiring, improve noise immunity, increase reliability, and improve serviceability. Implementing all of the various changes which were proposed is a very time consuming task. The decision to mount all of the positioning table components on one rack mountable panel is a step in this direction, as is the purchase of a power supply which will also be rack mounted. Although other changes may be necessary as research continues, the proposed block diagram for the redesigned system is shown in Fig. 2. The Head Drive and Control Assembly will contain the original Siemens driver board (modified to eliminate the unneeded circuits) and the pulse driver board which will contain the higher precision CMOS 'one-shots'. In addition to these circuits, the assembly will incorporate circuitry to allow the microprocessor to control which nozzles are on. There will still be a manual switch assembly which plugs into this assembly and makes it possible to switch on individual nozzles manually.

A break-down of the components which will be contained in the Positioning Table Assembly is shown in Fig. 3. Central to this assembly will be the Positioning Table Interface Board. It will consist of the LCD displays and the associated counter/drivers for each axis, the table initialization switch 'debounce' circuits and counter reset circuits, and the twelve inverters needed for the lines to and from the SCCS-85

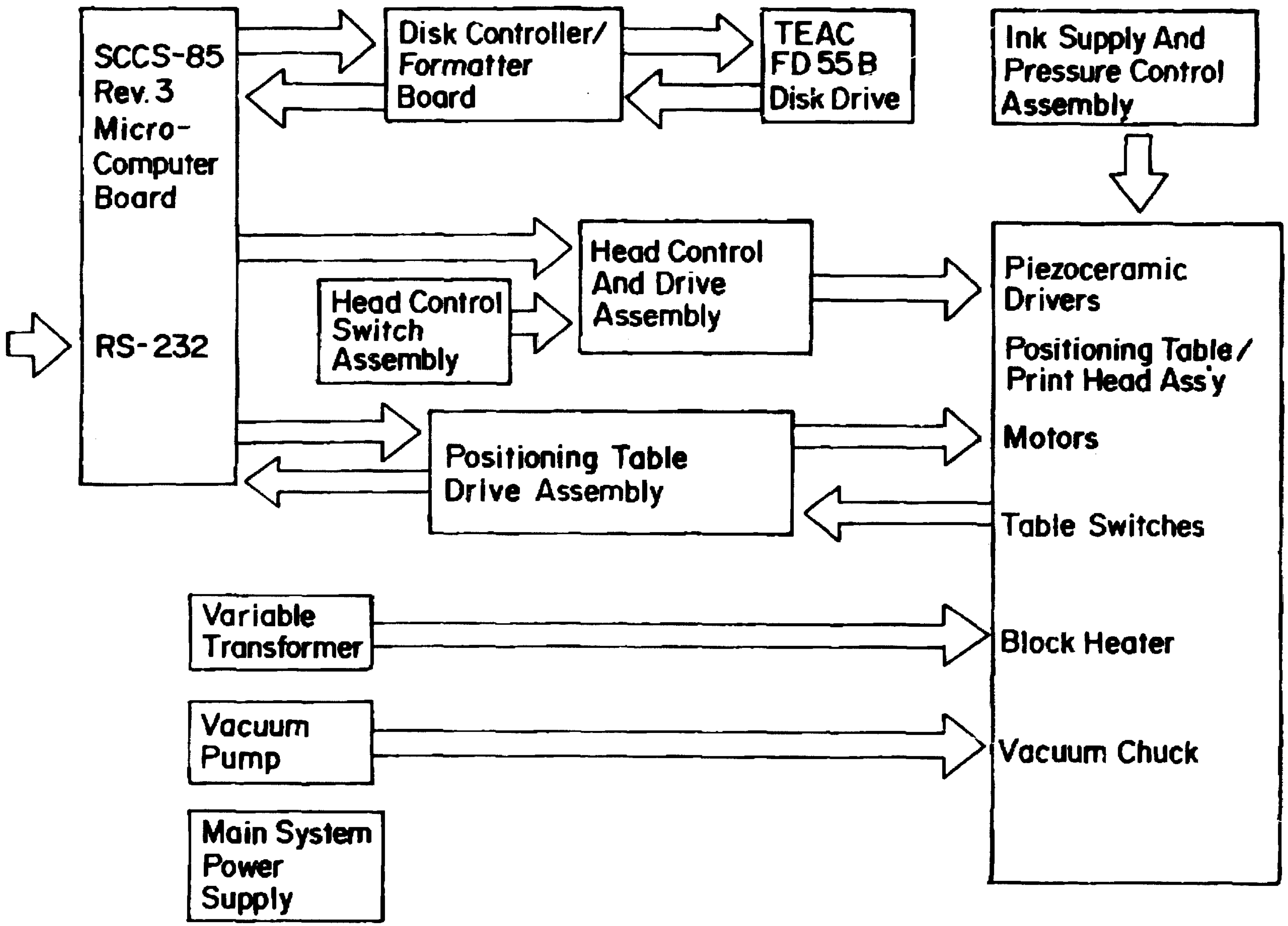


Figure 2 Ink Jet Printing System Block Diagram.

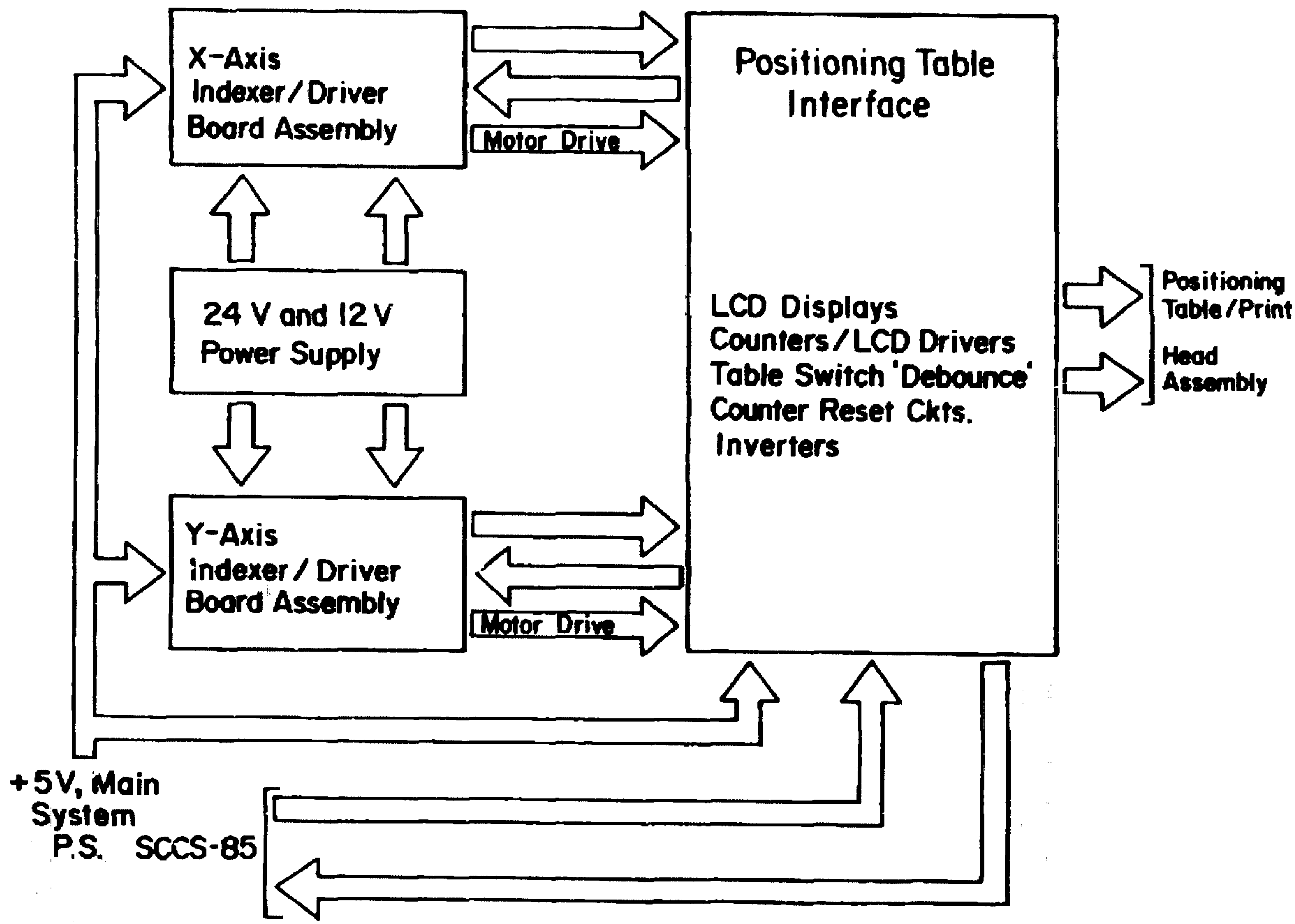


Figure 3 Positioning Table Drive Assembly.

board. The Positioning Table Interface Board will also serve as a connection point for the Indexer/Driver Board Assemblies and the Positioning Table and Print Head Assembly. This will make it possible to have a single cable from the Positioning Table Interface to the Positioning Table and Print Head Assembly. This cable will contain the motor drive signals for both motors and also the five necessary lines used for the table initialization switches. The +12 and +24 volt power supplies will be a part of this assembly, and the +5 volt source also needed on this assembly will come from the main power supply. By consolidating these components into one assembly, the wiring between it and the rest of the system is greatly simplified. Note that only a single 20 line cable will connect this assembly to the SCCS-85 board.

During this quarter, a photovoltaic cell test set-up available for this laboratory's use was investigated. It is a relatively simple set-up consisting of a probing station with a vacuum chuck connected to a Tektronix model 576 curve tracer. There is also a variable light source mounted above the sample area. It provides a general qualitative analysis of the current-voltage curves for photovoltaics, both darkened and illuminated, but was not intended for critical analysis. Nonetheless, it will serve as a means of doing basic cell evaluation during the next months to determine the effects of changes in printing parameters, ink chemistry, and firing procedures.

2.3 Computer Aided Design and Programming

The model 4106 color graphics terminal recently acquired from Tektronix, Inc. has been a valuable addition to Turner Laboratory's equipment. It was chosen because of its compatability to the in house 'CMASK' circuit design program. The 4106 is a microprocessor-controlled terminal having a 13-inch color display screen with a 640 x 480 pixel resolution. Both dialog and graphics can be dealt with simultaneously on the screen in a variety of available colors. This unit also features a 4096 x 4096 addressable terminal space coordinate system and multilevel displays of complex information. It operates in a variety of modes allowing it to be used as a stand- alone graphics system and also as an interactive unit, providing both screen editing and graphics capabilities in conjunction with a host computer system.

The 'CMASK' design program was specifically written for the Tektronix model 4113 terminals; however, with the exception of a few minor details, the model 4106 is compatible with the program. This design program was developed at Purdue University, and is almost continually undergoing changes. Work will continue on learning 'CMASK' design techniques with the latest version of the program. More importantly, time will be devoted to learning how to use 'CMASK' and the 4106 to meet the required needs of the ink jet printing system. This task will continue over the next months as it will probably involve a large amount of additional software development. It is not the actual design of the circuit on the terminal, but the movement of that design information from the terminal to the SCCS-85 microcomputer board that is difficult.

General programming development for the ink jet printing system also continued. As part of the preliminary printing studies which were carried out this quarter, some experimentation was conducted using different head triggering frequencies. Most of the printing studies in the past used a head triggering frequency of 100 Hz, but higher frequencies were required to get thicker films This involved some minor programming changes since the head triggering signal is now being generated on the SCCS-85 board's Timer Group.

In an effort to achieve one of the future system goals of increasing the printing speed, two different programming changes were tried. The existing program is set up in such a way that printing occurs in the positive X direction and in the positive Y direction on the substrate, but not in the negative directions. A new program was written which allows the head to print in both directions of both axes. Along with this programming change, the pattern program also had to be changed accordingly. This program will require some further refinements before it will be implemented on a permanent basis, but the technique works and will help to reduce print time.

Secondly, some experimental programs were written to run the positioning table at higher stepping speeds. This involved making use of the acceleration and deceleration features built into the Superior Electric indexer board's logic. This is a more complex problem because it involves not only the table movement, but the coordination of the movements with the head triggering frequency. In the past, the table has moved at one set base speed, so there was always a definite ratio between the stepping frequency and head triggering frequency. However, with acceleration and deceleration programmed into table moves, the head triggering frequency must be ramped up and ramped down accordingly For a consistent line to be printing. Programming work will be continuing to accomplish this task. This task will possibly also involve some electronic hardware additions.

2.4 Printing Studies

Ink jet film printing studies were started this quarter. Various inks were studied and several different head triggering frequencies, table speeds, nozzle diameters, and piezolectric driver pulse amplitudes were tried.

Three different ink solvents were tried: xylene, toluene, and tetrahydrafuran (THF). Siler neodecanoate was dissolved in these three solvents to form the inks (SI-1, SI-2, SI-3 and SI-4). In the future when the laboratory is equipped with a proper exhaust system, benzene may be tried. Due to its extremely toxic nature, it will not be used until the proper safety precautions have been taken.

The silver neodecanoate used in these inks was prepared following the reactions:

$$R_3 - \underset{\displaystyle R_2}{\overset{\displaystyle R_1}{\underset{|}{\overset{|}{C}}}} - COOH + NH_4OH \dashrightarrow R_3 - \underset{\displaystyle R_2}{\overset{\displaystyle R_1}{\underset{|}{\overset{|}{C}}}} - COONH_4 + H_2O$$

$[R_1 + R_2 + R_3 = C_8H_{19}]$

$$
\begin{array}{ccccccccc}
 & R_1 & & & & & R_1 & & \\
 & | & & & & & | & & \\
R_3 - & C & - COONH_4 + AgNO_3 & \dashrightarrow & R_3 - & & C & - COOAg + NH_4NO_3 & \\
 & | & & & & & | & & \\
 & R_2 & & & & & R_2 & &
\end{array}
$$

An equimolecular mixture of 95% pure neodecanoic acid (9.46 gm = 0.055 mole) and 58% ammonium hydroxide (3.31 gm = 0.055 mole) were mixed together at room temperature and the resulting soap was diluted in deionized water (50 ml). An aqueous solution of silver nitrate (10 gm = 0.0526 mole) (water = 50 ml) was then added slowly with stirring. The white precipitate of silver neodecanoate thus formed was repeatedly washed with cold and warm (30-50°C) deionized water. The solid was mixed with methanol (100 ml) and stirred for final drying and purification and then suction filtered. Silver neodecanoate was then isolated in 70% yield as a white dry solid.

The physical data for the solvents and inks are shown in Table 1 and Table 2. Density was determined using a specific gravity bottle, surface tension was recorded using a CENCO-duNOUY tensiometer, viscosity was measured using an Ostwald-kinematic viscometer. The boiling points of xylene, toluene, benzene, and THF are quite different from each other and their rates of vaporization at a given temperature are equally varied. How these differing characteristics affect the printing of the films was investigated.

Various head triggering frequencies were tried for each of the three different solvents. For all the tests, the substrate was moving

Table 1. Physical Data of Solvents at 23°C.

Solvent	Source	Boiling Point (°C)	Density (gm/cc)	Viscosity (cp)	Surface Tension dynes/cm
THF	Fisher Scientific	67	0.886	0.461	28.0
Benzene	Mallinckrodt	80	0.87	0.652	28.8
Toluene	Aldrich	111	0.86	0.59	28.5
Xylene	Aldrich	138	0.86	0.65	28.2

Table 2. Physical Data of Silver Inks at 23°C.

Ink No.	Solvent	wt/o Ag by TGA	Density (gm/cc)	Viscosity (cp)	Surface Tension dynes/cm
SI-1	xylene	20.8	1.143	5.37	30.0
SI-2	toluene	19.2	1.103	3.8	26.4
SI-3	THF	21.2	not determined		
SI-4	THF	16.8	1.070	1.44	25.7

at a constant velocity of 1.016 cm/sec. For each pulse applied to a head driver, one droplet of ink was ejected down onto the substrate. Obviously then, a 200 Hz head triggering signal will deposit twice the amount of ink in a specified length of table travel as does a head signal of 100 Hz. Thicker films tend to yield lower sheet resistance values which is a parameter that should be minimized in order to minimize series resistance of the cells. However, as head frequency is increased and greater amounts of ink are deposited onto the substrate, line definition tends to be degraded.

The first ink studied was about a 50% solution of silver neodecanoate in xylene (SI-1). The substrates used in these tests were AlSiMag 838 because no Si cells were available. Since the substrate was maintained at a temperature of about 35°C, the vaporization rate was low for this ink. At the lower frequencies, the line definition for the films was good, but at the line definition got progressively worse at frequencies above 300 Hz. This was due to the fact that as more material was put down, spreading occurred because the solvent did not evaporate quickly enough. Table 3 shows the qualitative line definition ratings for the various frequencies used.

Table 3. Line Definition Quality

Ink No.	Solvent	Frequency (Hz) 100	200	300	400	500	600
SI-1	Xylene	****	***	**	*	*	*
SI-2	Toluene	****	****	***	**	**	**
SI-4	THF	****	****	****	****	***	***

**** excellent

*** good

** fair

* poor

The second ink studied was about a 50% solution of silver neodecanoate in toluene (SI-2). The boiling point of toluene is 27°C lower than xylene, therefore the vaporization rate of this solvent is considerably higher that the rate for xylene. Frequencies from 100-600 Hz were tried, and the results in Table 3 show that the line definition at the higher frequencies was better with toluene than it was with xylene solvent.

The last ink studied was about a 40% solution of silver neodecanoate in THF (SI-4). Prior to this, about a 50% solution of silver neodecanoate in THF (SI-3) was used. Due to the very low boiling point of THF (67°C), the rate of vaporization was very fast, and when the ink was exposed to air a thin coating formed on the surface. The diluted ink (SI-4) seemed to minimize this problem and so was used for this test. Frequencies from 100-600 Hz were again used. The line definition was especially good at the higher head trigger frequencies, such as 400 and 500 Hz. The wet film surfaces were a little rough, but became smooth after firing. The results for the various frequencies with this ink are also listed in Table 3.

For the xylene ink solution (SI-1), the best line definition was with head triggering frequency of 100 Hz. Multilayer films were printed at this frequency, thus increasing film thickness without increasing head frequency. Both the line definition and the film thickness were very good.

Since the number of solar cells available was very limited, most of the printing studies were done on alumina substrates. However, the surface properties of the silicon solar cells were quite different from those of alumina substrates. From an interfacial energy point of view, the solid-ink interfacial energy of the silicon solar cell was larger than that of the alumina giving the sessile drop configurations depicted in Fig. 4. Such phenomena of contracting the ink to the center line was very desirable because is gave better line definition, narrower and thicker lines on the solar cells.

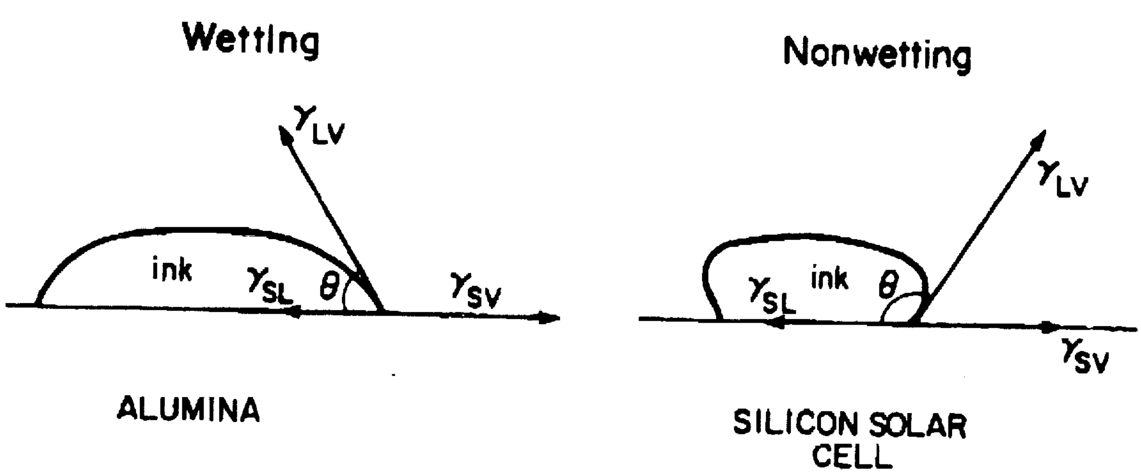


Figure 4 Interfacial Energies with Alumina and Silicon Substrates.

Some printed solar cells were evaluated using the TENCOR profilometer. The thickness distribution of the cross section of a lin is shown in Fig. 5. The surface of solar cell was rough, and the ink jet printing method gave a uniform thickness which replicated the surface roughness. This is in contrast to screen printing, which tends to fill the surface roughness and produce a smoother film. The two cases are contrasted in Fig. 6.

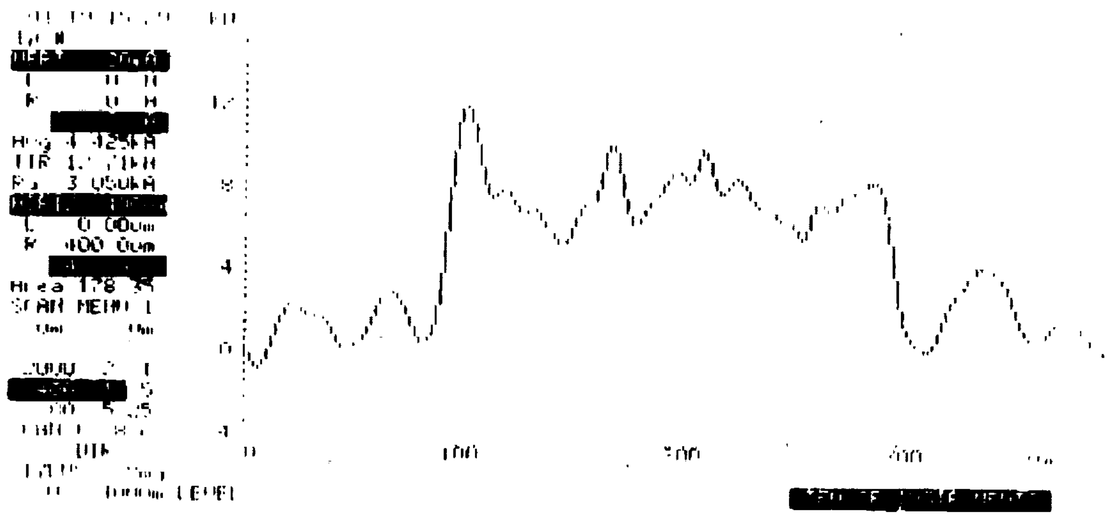


Figure 5 Film Thickness Cross Section.

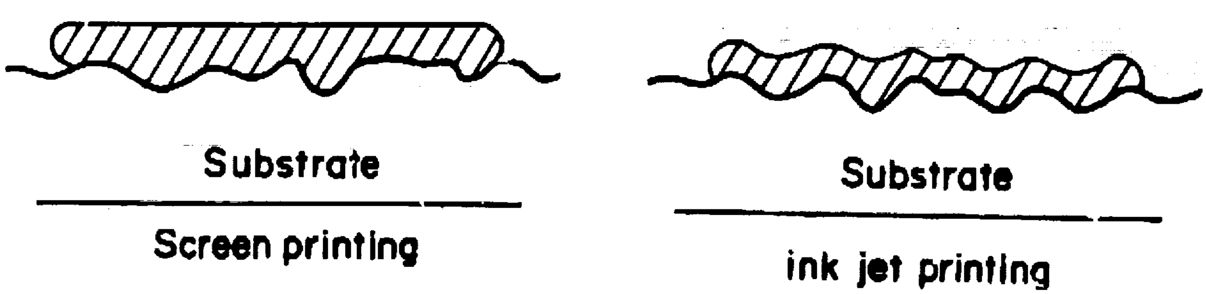


Figure 6 Comparison of Screen Printing and Ink Jet Printing on a Rough Surface.

If the ink jet driver pulse was too large or if the ink jet head was too close to the substrate, a double peak printed film was observed. The phenomena was due to the effect depicted in Fig. 7.

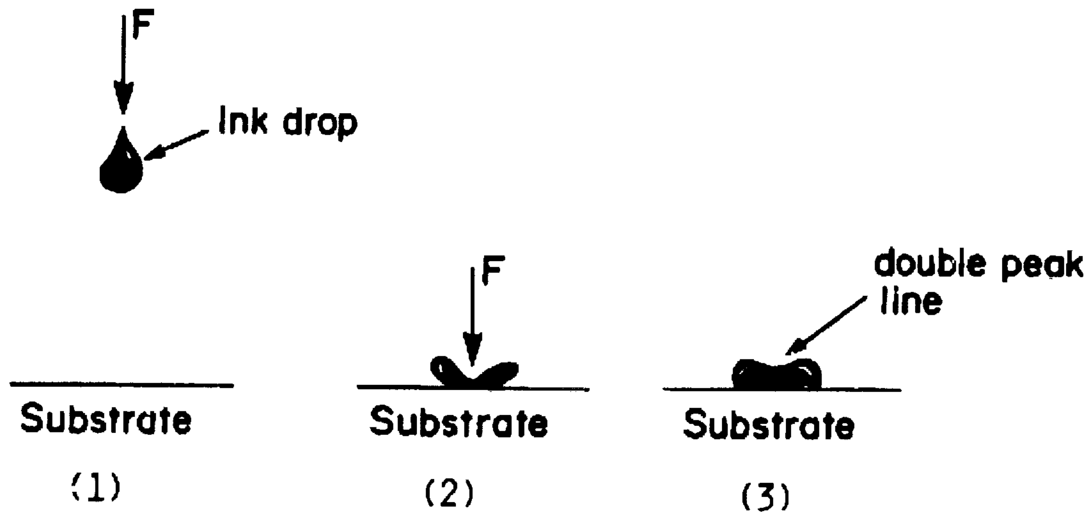


Figure 7 Growth of Double Peak Line.

When ink drops are ejected from the ink jet nozzle, they are acted on by the force from the piezoelectric material contraction. As the ink drops hit the substrate, this force splits the drops into two and pushes the segments to each side. The force is dissipated at that moment, and the two split drops try to flow back to the center. However, the solvent evaporates before they can level and leaves double peaks. This phenomena was undesirable because it gave less uniform lines. This problem can be solved by adjusting the distance between the ink jet head and the substrate and the pulse voltage.

The pulse voltage of the ink jet driver was varied with all other parameters kept constant. It was determined that there existed a threshold voltage, below which no ink could be ejected. Above the threshold voltage, the ink jet drops became larger and the printed line was thicker as the pulse voltage increased. At larger pulse voltages, double peak printed lines were observed as discussed in the previous paragraph.

The original ink jet head was equipped a nozzle plate with twelve 3 mil diameter holes, which controlled the size of the ink jet drops. A new nozzle plate with different hole sizes was made by JPL and installed on the ink jet head. The sizes of the orfices were 0.5, 1, 2, 3, 4, and 5 mil. Experiments showed that the different hole sizes required different ink jet threshold voltages. With increased diameter of the holes, the printed lines became thicker. However, no ink was ejected from the 0.5 or 1 mil orifices for any pulse voltage. The experiments were done at 200 Hz ink jet head frequency, and further experiments will be conducted at lower frequencies to investigate the small holes. It is possible that ink can be ejected from the small holes at lower frequencies.

During the printing experiments, it was found that the ink drop at ink jet nozzle grew larger during jogging movement, (moving the substrate to a certain position without printing). The reason for this problem was the combination of the low viscosity of the ink, and the pressure inside the ink system. This collected larger ink drop was deposited onto the initial spot of the next printing line, which made for poor line definition at the initial spot. It was observed that a shorter jogging movement improved the problem. Since the original software program was written in such a way that printing was only excuted in one direction and jogging in another direction, the jogging movement required an excessive amount of time. In order to solve the problem, the original software program was modified so that printing could be excecuted in either direction. This modified program made the jogging movement shorter, and the line definition of the initial spot of each line was improved.

The movement of the substrate is controlled by the x-y table, and the speed of the table can be varied through the software program. By changing the speed of the table, different thickness of film can be obtained. Under normal conditions, the base speed of the x-y table was 1 cm/s. If the base speed was changed to 0.5 cm/s the film thickness was doubled, and changing the table speed to 2 cm/s gave a film thickness half of the original. However, if the table speed was adjusted to a very low or a very high speed, the stepper motor went into a resonant and unstable condition. Some hardware changes are needed to return the machine to a stable condition again.

3. PLANS

In the coming quarter, a major emphasis will be placed upon finishing the electronic modifications already decided upon. One of these is finishing the construction of the Positioning Table rack assembly. This will include the new LCD displays to indicate table position and the additional circuitry for resetting the counters in conjunction with table initialization. This change will also reduce the amount of interwiring between the microcomputer board and table drive electronics.

A second major electronic change which will be concentrated on is the implementation of the disk drive system. The disk controller/formatter board will have to be fabricated and appropriate software for the disk operating system will have to be implemented into the system. This will be a major task of this next quarter because it involves significant changes in both hardware and software. Along with this change, the new power supply will be remounted on a standard rack panel and incorporated into the system.

Thirdly, work will be continuing on constructing a new pulse driver board which will contain the higher precision 'one-shot' circuits. It will also contain the new circuitry for controlling the nozzle selection through programming. Significant programming development will be involved before the system will be capable of using multiple nozzles.

Much of the preliminary work has been done toward making it possible to use a computer aided design system with the ink jet printing system. The acquisition of the Tektronix 4106 terminal has allowed the use of Engineering Computer Network's 'CMASK' program which has the design capabilities needed for the ink jet system. However, the job of interpreting screen information and putting it in a form (through programming) that the SCCS-85 can convert to appropriate move commands is complex. The methods and techniques of accomplishing this will continue to be investigated and programs developed accordingly.

The preliminary printing studies started during this quarter will be continuing throughout this next quarter. Much more work will be done in investigating how the various parameters involved in the printing process affect the printed film. Some of these will involve the continued investigation into various ink solvents and the possible addition of compounds to improve film adhesion. Also, work will be moving forward in trying to increase film thickness and still maintain good line definition.

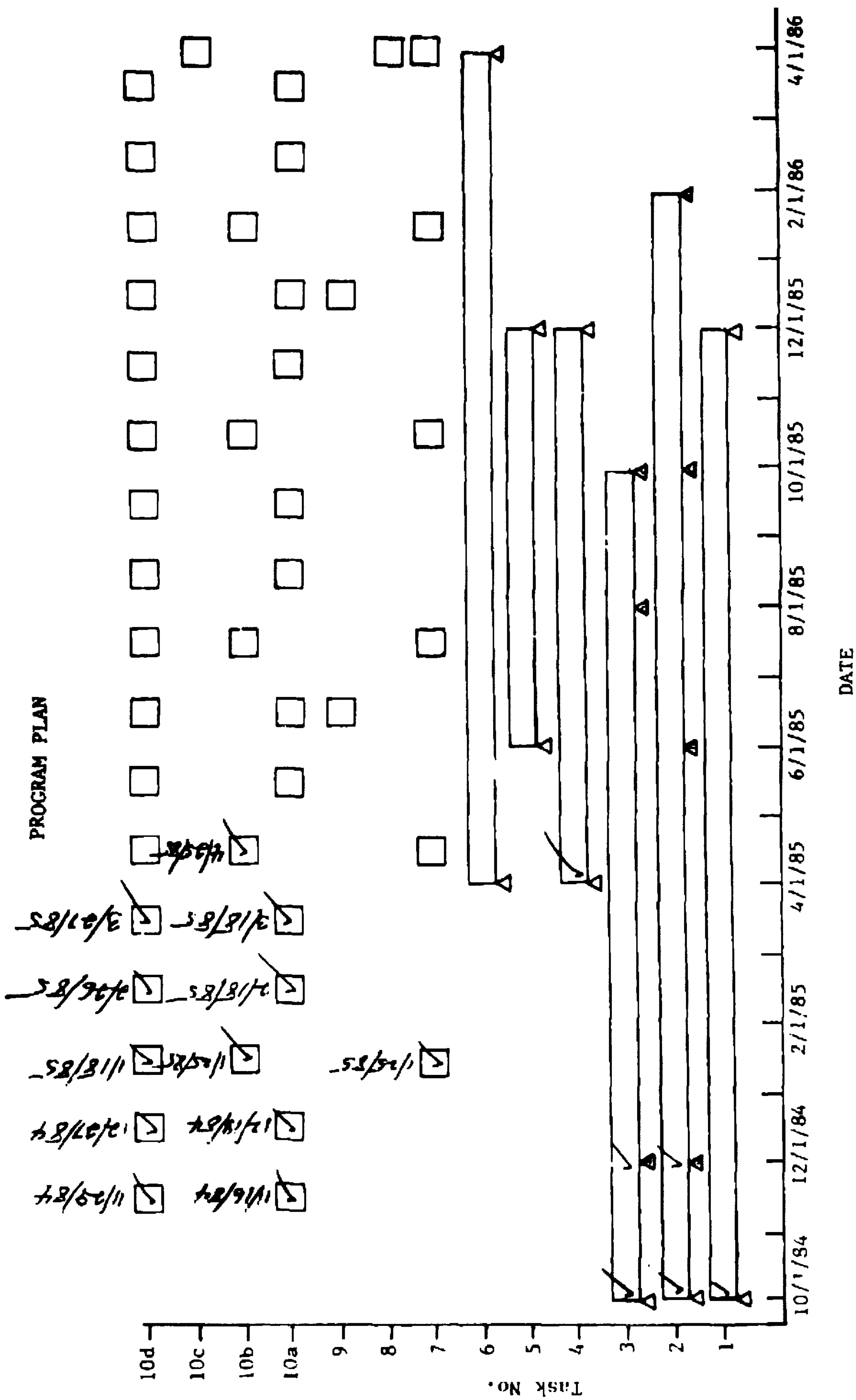
During this next quarter work will be started to evaluate how the various printing parameters affect the cells' characteristics. The test set-up now available to the Turner Laboratory will make it possible to compare cells, even though it will not allow actual quantitative evaluation. As the ink jet printing system is refined further and the modifications put in place, it will be easier to vary single printing parameters in order to optimize each and thus produce a more efficient solar cell.

4. SCHEDULE

The list of tasks and updated program plan are attached.

LIST OF TASKS

1. Ink Development and Processing Studies
2. Electronic Modifications and Programming
   a. Design modification studies
   b. Electronic assembly
   c. Operational demonstration
   d. Computer software generation
3. Mechanical Modifications
   a. Design modification studies
   b. Mechanical assembly
   c. Operational demonstration
4. Film Thickness and Line Width Studies
5. Printing Speed Studies
6. Fabricating and Characterizing Cells
7. Specifications
8. Data for Economic Evaluation
9. Personnel for Meetings
10. Documentation
    a. Monthly technical reports
    b. Quarterly technical reports
    c. Final technical report
    d. Monthly financial reports


PROGRAM PLAN
Task No.
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